

# Optimal entanglement concentration for quantum dot and optical microcavities systems

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A recent paper [Chuan Wang, Phys. Rev. A **86**, 012323 (2012)] discussed an entanglement concentration protocol (ECP) for partially entangled electrons using a quantum dot and microcavity coupled system. In his paper, each two-electron spin system in a partially entangled state can be concentrated with the assistance of an ancillary quantum dot and a single photon. In this paper, we will present an optimal ECP for such entangled electrons with the help of only one single photon. Compared with the protocol of Wang, the most significant advantage is that during the whole ECP, the single photon only needs to pass through one microcavity which will increase the total success probability if the cavity is imperfect. The whole protocol can be repeated to get a higher success probability. With the feasible technology, this protocol may be useful in current long-distance quantum communications.

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## I. INTRODUCTION

Entanglement plays an important role in current quantum information processing [1, 2]. For most of the practical quantum communication and computation protocols, the maximally entangled states are usually required. For example, quantum key distribution [2, 3], quantum teleportation [4], quantum secret sharing [5–7], quantum secure direction communication [8–10] and quantum dense coding [11] all need entanglement to set up the quantum channels. However, the entanglement channel will inevitably decrease because it always contacts the environment. The degraded entanglement will decrease the fidelity of the teleportation, or make some quantum communication protocols insecure. Therefore, people should seek for effective ways to combat noise and recover the entanglement to a high quality.

Entanglement concentration [12–24] is one of the powerful methods which is used to improve the quality of the entanglement. It can distill a subset system in a maximally entanglement state from a set of systems in a partially entangled (less-entangled) pure state. In 1996, Bennett *et al.* proposed an entanglement concentration protocol (ECP) based on the Schmidt decomposition [12]. In the protocol, some collective measurements are needed, which are hard to manipulate in experiment at present. Bose *et al.* proposed an ECP based on entangle-

ment swapping [13]. Later, this method was developed by Shi *et al.* with collective unitary evaluation [14]. Zhao *et al.* and Yamamoto *et al.* proposed two similar ECPs with linear optics independently [15, 16]. In 2008, ECPs based on the cross-Kerr nonlinearity was proposed [17].

Currently, most of the ECPs are focused on photons, for photons are the best candidate for optical transmission. Actually, quantum communication and computation can also be achieved with solid electrons [25–35]. For example, In 2004, Beenakker *et al.* showed that with the help of charge degree of freedom, they could brake through the obstacle of the no-go theorem and construct a CNOT gate [25]. Moreover, Waks and Vuckovic discussed the interaction of a cavity with a dipole [26]. The cavity decay rate is larger than the vacuum Rabi frequency. It has been used to construct a quantum repeaters in a weak-coupling regime [27, 28]. Wang *et al.* also proposed an ECP with electron-spin entangled states using quantum dot spins in optical microcavities [21]. Recently, he improved the protocol, and presented an efficient ECP with the help of an ancillary quantum dot and a single photon [22]. However, this protocol is still not an optimal one.

In this paper, we present an optimal ECP for electronic systems by exploiting a weak-coupling regime. In this protocol, only one pair of less-entangled pure state and a single photon are required. Compared with the conventional ECPs, this ECP resorts less original less-entangled pure state sources. It can also reach the same success probability as described in Ref. [21]. Moreover, it can be repeated to get a higher success probability.

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Compared with Ref. [22], we do not require the single quantum dot as an ancillary and only the single photon can complete the task. Moreover, the single photon only needs to pass through one microcavity, which will greatly improve the success probability in a practical situation.

This paper is organized as follows. In Sec. 2, we first briefly explain the basic element of this protocol, which is also shown in Ref. [21, 27]. In Sec. 3, an ECP assisted with single photon is described. In Sec. 4, we present a discussion and summary.

## II. BASIC ELEMENT FOR ECP

Before we start to explain our ECP, we first introduce the basic element of our protocol, as shown in Fig. 1. In Ref. [27], it can be used to perform the CNOT gate and the Bell-state analysis. It also has been discussed to implement the photon entangler, entanglement beam splitter, optical Faraday rotation [29–31]. Recently, Hu and Rarity also presented schemes for efficient state teleportation and entanglement swapping, using single quantum dot spin in the optical microcavity [32]. The single-electron-charged quantum dot in a resonator shows a good interaction between a photon and an electron spin. The photon and the electron can be used to generate the hybrid entanglement with the quantum dot coupled to a microcavity. From Fig. 1, if we consider the spin of the electron in spin up state  $|\uparrow\rangle$  and a photon in state  $s_z = +1$ , the circularly polarized light might change their polarization according to direction of propagation, and the spin of the electron, after the photon passing through the cavity. For example, if the propagation of the photon is in the direction of the  $z$  axis, and the polarization of the photon is right-circular-polarization, say  $|R^\uparrow\rangle$ , it will become  $|L^\downarrow\rangle$ , if the electron is  $|\uparrow\rangle$ . The total rules of the state change under the interaction of the photon with  $s_z = \pm 1$  can be described as [21, 27]

$$\begin{aligned} |R^\uparrow, \uparrow\rangle &\rightarrow |L^\downarrow, \uparrow\rangle, & |R^\downarrow, \uparrow\rangle &\rightarrow -|R^\downarrow, \uparrow\rangle, \\ |R^\uparrow, \downarrow\rangle &\rightarrow -|R^\uparrow, \downarrow\rangle, & |R^\downarrow, \downarrow\rangle &\rightarrow |L^\uparrow, \downarrow\rangle, \\ |L^\uparrow, \uparrow\rangle &\rightarrow -|L^\uparrow, \uparrow\rangle, & |L^\downarrow, \uparrow\rangle &\rightarrow |R^\uparrow, \uparrow\rangle, \\ |L^\uparrow, \downarrow\rangle &\rightarrow |R^\downarrow, \downarrow\rangle, & |L^\downarrow, \downarrow\rangle &\rightarrow -|L^\downarrow, \downarrow\rangle. \end{aligned} \quad (1)$$

Here  $|R\rangle$  and  $|L\rangle$  denote the states of right-circular-polarized and left-circular-polarized photons, respectively. The  $\uparrow$  and  $\downarrow$  on the superscript arrow are the propagation direction along the  $z$  axis.

## III. ECP ASSISTED WITH ONLY A SINGLE PHOTON

In this section, we will show that the single electron is not necessary, only a single photon can also complete this task, which leads it more optimal than the protocols in Refs. [21, 22].

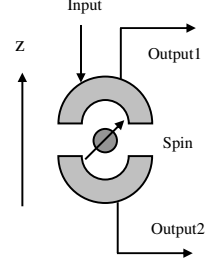


FIG. 1: A schematic drawing of the basic element of our ECP. The quantum dot spin is coupled in optical microcavities. Input represents the input port of a photon. Output1 and Output2 are the output ports of the photon after coupled with the electron-spin system.

Suppose Alice and Bob share the less-entangled state of the form

$$|\phi^+\rangle_{12} = \alpha|\uparrow\rangle_1|\uparrow\rangle_2 + \beta|\downarrow\rangle_1|\downarrow\rangle_2, \quad (2)$$

with  $|\alpha|^2 + |\beta|^2 = 1$ . The subscripts "1" and "2" are the spin 1 and spin 2 shown in Fig. 2. Alice prepares another single photon as

$$|\Phi\rangle_P = \alpha|R\rangle + \beta|L\rangle. \quad (3)$$

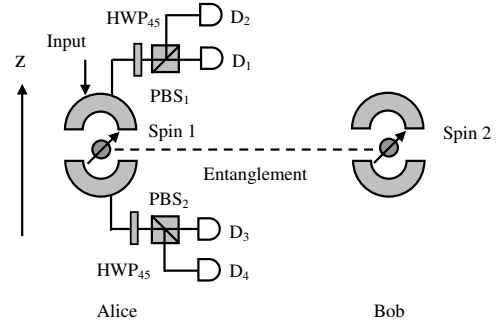


FIG. 2: A schematic drawing of the basic principle of our ECP. The PBSs are the polarization beam splitters. They are used to transmit the photon in  $|H\rangle$  polarization and reflect the photon in  $|V\rangle$  polarization.  $HWP_{45}$  is the quarter wave plate.

The less-entangled state combined with the single photon evolves as

$$\begin{aligned} |\Phi\rangle_P |\phi^+\rangle_{12} &= (\alpha|R^\downarrow\rangle + \beta|L^\downarrow\rangle) \\ &(\alpha|\uparrow\rangle_1|\uparrow\rangle_2 + \beta|\downarrow\rangle_1|\downarrow\rangle_2) \\ &= \alpha^2|R^\downarrow\rangle|\uparrow\rangle_1|\uparrow\rangle_2 + \beta^2|L^\downarrow\rangle|\downarrow\rangle_1|\downarrow\rangle_2 \\ &+ \alpha\beta(|R^\downarrow\rangle|\downarrow\rangle_1|\downarrow\rangle_2 + |L^\downarrow\rangle|\uparrow\rangle_1|\uparrow\rangle_2) \\ &\rightarrow -\alpha^2|R^\downarrow\rangle|\uparrow\rangle_1|\uparrow\rangle_2 - \beta^2|L^\downarrow\rangle|\downarrow\rangle_1|\downarrow\rangle_2 \\ &+ \alpha\beta(|L^\uparrow\rangle|\downarrow\rangle_1|\downarrow\rangle_2 + |R^\uparrow\rangle|\uparrow\rangle_1|\uparrow\rangle_2). \end{aligned} \quad (4)$$

Alice then lets her photon pass through the quarter wave plate (HWP<sub>45</sub>), which makes  $|H\rangle = \frac{1}{\sqrt{2}}(|R\rangle + |L\rangle)$ , and  $|V\rangle = \frac{1}{\sqrt{2}}(|R\rangle - |L\rangle)$ .  $|H\rangle$  and  $|V\rangle$  represent the horizontal and vertical polarization, respectively. Obviously, the items  $-\alpha^2|R^\perp\rangle|\uparrow\rangle_1|\uparrow\rangle_2$  and  $-\beta^2|L^\perp\rangle|\downarrow\rangle_1|\downarrow\rangle_2$  will make the detectors D<sub>3</sub> or D<sub>4</sub> fire, while the items  $|L^\uparrow\rangle|\downarrow\rangle_1|\downarrow\rangle_2$  and  $|R^\uparrow\rangle|\uparrow\rangle_1|\uparrow\rangle_2$  will make the conventional single-photon detectors D<sub>1</sub> or D<sub>2</sub> fire. Therefore, after passing through the HWP<sub>45</sub>, the state  $\frac{1}{\sqrt{2}}(|L^\uparrow\rangle|\downarrow\rangle_1|\downarrow\rangle_2 + |R^\uparrow\rangle|\uparrow\rangle_1|\uparrow\rangle_2)$  will become

$$\begin{aligned} & \frac{1}{\sqrt{2}}(|L^\uparrow\rangle|\downarrow\rangle_1|\downarrow\rangle_2 + |R^\uparrow\rangle|\uparrow\rangle_1|\uparrow\rangle_2) \\ \rightarrow & \frac{1}{2}(|H\rangle - |V\rangle)|\downarrow\rangle_1|\downarrow\rangle_2 + \frac{1}{2}(|H\rangle + |V\rangle)|\uparrow\rangle_1|\uparrow\rangle_2 \\ = & \frac{1}{\sqrt{2}}|H\rangle\frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\uparrow\rangle_2 + |\downarrow\rangle_1|\downarrow\rangle_2) \\ + & \frac{1}{\sqrt{2}}|V\rangle\frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\uparrow\rangle_2 - |\downarrow\rangle_1|\downarrow\rangle_2). \end{aligned} \quad (5)$$

Finally, after passing through the PBS<sub>1</sub>, which transmits the  $|H\rangle$  polarization photon and reflects the  $|V\rangle$  polarization photon, they will obtain  $\frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\uparrow\rangle_2 + |\downarrow\rangle_1|\downarrow\rangle_2)$  if D<sub>1</sub> fires, and obtain  $\frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\uparrow\rangle_2 - |\downarrow\rangle_1|\downarrow\rangle_2)$ , if D<sub>2</sub> fires. The success probability is  $2|\alpha\beta|^2$ .

Interestingly, from Eq. (4), it has another case that the photon will be in another output mode, which makes the original state collapse to  $\alpha^2|R^\perp\rangle|\uparrow\rangle_1|\uparrow\rangle_2 + \beta^2|L^\perp\rangle|\downarrow\rangle_1|\downarrow\rangle_2$ . After passing through the HWP<sub>45</sub> and PBS<sub>2</sub>, if the detector D<sub>3</sub> fires, they will obtain  $\alpha^2|\uparrow\rangle_1|\uparrow\rangle_2 + \beta^2|\downarrow\rangle_1|\downarrow\rangle_2$ , and if the D<sub>4</sub> fires, they will obtain  $\alpha^2|\uparrow\rangle_1|\uparrow\rangle_2 - \beta^2|\downarrow\rangle_1|\downarrow\rangle_2$ . Both of them are the less-entangled states, and can be reconcentrated into a maximally entangled pair in the second concentration round. Briefly speaking, if they get

$$|\phi^+\rangle'_{12} = \alpha^2|\uparrow\rangle_1|\uparrow\rangle_2 + \beta^2|\downarrow\rangle_1|\downarrow\rangle_2. \quad (6)$$

Alice only needs to choose another single photon of the form

$$|\Phi\rangle'_P = \alpha^2|R\rangle + \beta^2|L\rangle. \quad (7)$$

So the whole system can be written as

$$\begin{aligned} & |\phi^+\rangle'_{12}|\Phi\rangle'_P \\ = & (\alpha^2|\uparrow\rangle_1|\uparrow\rangle_2 + \beta^2|\downarrow\rangle_1|\downarrow\rangle_2)(\alpha^2|R^\perp\rangle + \beta^2|L^\perp\rangle) \\ = & \alpha^4|\uparrow\rangle_1|\uparrow\rangle_2|R^\perp\rangle + \beta^4|\downarrow\rangle_1|\downarrow\rangle_2|L^\perp\rangle \\ + & \alpha^2\beta^2(|\uparrow\rangle_1|\uparrow\rangle_2|L^\perp\rangle + |\downarrow\rangle_1|\downarrow\rangle_2|R^\perp\rangle) \\ \rightarrow & -\alpha^4|R^\perp\rangle|\uparrow\rangle_1|\uparrow\rangle_2 - \beta^4|L^\perp\rangle|\downarrow\rangle_1|\downarrow\rangle_2 \\ + & \alpha^2\beta^2(|L^\uparrow\rangle|\downarrow\rangle_1|\downarrow\rangle_2 + |R^\uparrow\rangle|\uparrow\rangle_1|\uparrow\rangle_2). \end{aligned} \quad (8)$$

Obviously, from Eq. (8), following the same principle described above, the photon will pass through the optical cavity and will be detected. If the detectors D<sub>1</sub> or D<sub>2</sub>

fires, they will obtain the maximally entangled pair. The success probability is  $\frac{2|\alpha\beta|^4}{|\alpha|^4 + |\beta|^4}$ . If the detectors D<sub>3</sub> or D<sub>4</sub> fires, they will obtain another less-entangled pair of the form

$$|\phi^\pm\rangle''_{12} = \alpha^4|\uparrow\rangle_1|\uparrow\rangle_2 \pm \beta^4|\downarrow\rangle_1|\downarrow\rangle_2. \quad (9)$$

It is still a less-entangled state which can also be reconcentrated for the third round. In this way, by repeating the ECP, they can obtain a higher success probability than other ECPs. The success probability in each concentration round can be written as

$$\begin{aligned} P_1 &= 2|\alpha\beta|^2. \\ P_2 &= \frac{2|\alpha\beta|^4}{|\alpha|^4 + |\beta|^4}. \\ P_3 &= \frac{2|\alpha\beta|^8}{(|\alpha|^4 + |\beta|^4)(|\alpha|^8 + |\beta|^8)}, \\ &\dots\dots\dots \\ P_K &= \frac{2|\alpha\beta|^{2^K}}{(|\alpha|^4 + |\beta|^4)(|\alpha|^8 + |\beta|^8) \dots (|\alpha|^{2^K} + |\beta|^{2^K})}. \end{aligned} \quad (10)$$

Actually, the realization of this ECP relies on the efficiency of transmission and reflection for electrons and photon described in Sec. 2. We can calculate the practical transmission and reflection coefficients, according to Heisenberg equations of motion for the cavity-field operator and the trion dipole operator in weak excitation approximation. The reflection and transmission coefficients can be written as

$$\begin{aligned} r(\omega) &= 1 + t(\omega), \\ t(\omega) &= \frac{-\kappa[i(\omega_{X^-} - \omega) + \frac{\gamma}{2}]}{[i(\omega_{X^-} - \omega) + \frac{\gamma}{2}][i(\omega_c - \omega) + \kappa + \frac{\kappa_s}{2}] + g^2}, \end{aligned} \quad (11)$$

where  $g$  represents the coupling constant.  $\frac{\gamma}{2}$  is the  $X^-$  dipole decay rate.  $\kappa$  and  $\kappa_s/2$  are the cavity field decay rate into the input and output modes and the leaky rate, respectively [30]. In the approximation of weak excitation,  $\omega_c = \omega_{X^-} = \omega_0$ , and  $g = 0$ , we can get the reflection and transmission coefficients as

$$\begin{aligned} r_0(\omega) &= \frac{i(\omega_0 - \omega) + \frac{\kappa_s}{2}}{i(\omega_0 - \omega) + \frac{\kappa_s}{2} + \kappa}, \\ t_0(\omega) &= \frac{-\kappa}{i(\omega_0 - \omega) + \frac{\kappa_s}{2} + \kappa}. \end{aligned} \quad (12)$$

Here the  $\omega_0$ ,  $\omega_c$  and  $\omega_{X^-}$  are the frequencies of the input photon, cavity mode, and the spin-dependent optical transition, respectively. The transmission and reflection operators can be rewritten as

$$\begin{aligned} \hat{t}(\omega) &= t_0(\omega)(|R\rangle\langle R| \otimes |\uparrow\rangle\langle\uparrow| + |L\rangle\langle L| \otimes |\downarrow\rangle\langle\downarrow|) \\ &\quad + t(\omega)(|R\rangle\langle R| \otimes |\uparrow\rangle\langle\uparrow| + |L\rangle\langle L| \otimes |\downarrow\rangle\langle\downarrow|), \\ \hat{r}(\omega) &= r_0(\omega)(|R\rangle\langle R| \otimes |\uparrow\rangle\langle\uparrow| + |L\rangle\langle L| \otimes |\downarrow\rangle\langle\downarrow|) \\ &\quad + r(\omega)(|R\rangle\langle R| \otimes |\uparrow\rangle\langle\uparrow| + |L\rangle\langle L| \otimes |\downarrow\rangle\langle\downarrow|). \end{aligned} \quad (13)$$

Therefore, we can recalculate the success probability in each concentration round as

$$\begin{aligned}
 P'_1 &= \frac{|r(\omega)|}{\sqrt{|r_0(\omega)|^2 + |r(\omega)|^2}} P_1. \\
 P'_2 &= \frac{|t_0(\omega)|}{\sqrt{|t_0(\omega)|^2 + |t(\omega)|^2}} \frac{|r(\omega)|}{\sqrt{|r_0(\omega)|^2 + |r(\omega)|^2}} P_2. \\
 P'_3 &= \left( \frac{|t_0(\omega)|}{\sqrt{|t_0(\omega)|^2 + |t(\omega)|^2}} \right)^2 \frac{|r(\omega)|}{\sqrt{|r_0(\omega)|^2 + |r(\omega)|^2}} P_3. \\
 &\dots\dots \\
 P'_K &= \left( \frac{|t_0(\omega)|}{\sqrt{|t_0(\omega)|^2 + |t(\omega)|^2}} \right)^{K-1} \frac{|r(\omega)|}{\sqrt{|r_0(\omega)|^2 + |r(\omega)|^2}} P_K.
 \end{aligned} \tag{14}$$

The total success probability can be written as

$$P_t = P'_1 + P'_2 + \dots = \sum_{K=1}^{\infty} P'_K. \tag{15}$$

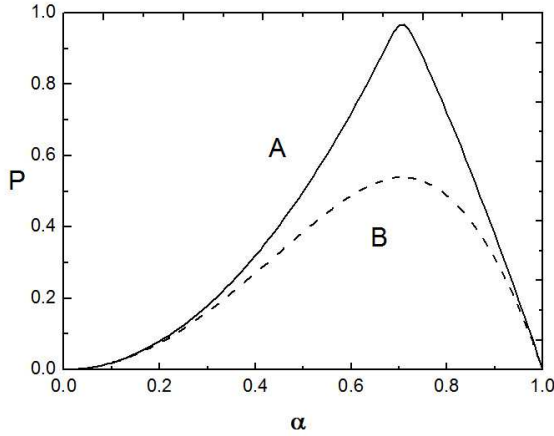


FIG. 3: Success probability  $P$  for obtaining a maximally entangled state after performing this ECP is altered with the initial coefficient  $\alpha \in (0, 1)$ . Curve A is the ideal case with no leakage. Curve B is the success probability with  $\kappa_s = 0.5\kappa$ ,  $g = 0.5\kappa$  and  $\gamma = 0.1\kappa$ . For numerical simulation, we let  $K = 5$  as a good approximation.

We calculate the total success probability in both the ideal case with no leakage and with  $\kappa_s = 0.5\kappa$ ,  $g = 0.5\kappa$  and  $\gamma = 0.1\kappa$ . In Fig. 3, it is shown that in the ideal case, the success probability can reach the maximally value 1 when  $\alpha = \frac{1}{\sqrt{2}}$ . However, the leakage of the cavity will decrease the success probability. We show that the maximum value of  $P$  is about 0.5 when  $\kappa_s = 0.5\kappa$ . For numerical simulation, we let  $K = 5$  as a good approximation.

#### IV. DISCUSSION AND SUMMARY

So far, we have fully explained our ECP. In our ECP, we exploit a single charged quantum dot inside an optical

cavity. This single charged quantum dot can be implemented by GaAs/InAs interface quantum dot. Therefore, we require the long coherent time of the quantum dot and the strong coupling of the quantum dot with the cavity to ensure the photon can be fully coupled with quantum dot. Fortunately, current experiment showed that the coherence time is long enough of the GaAs- or InAs-based quantum dots [33]. Moreover, current experiments also showed that the strong coupling has also been observed in different systems [36–38].

It is interesting to compare this ECP with other ECPs. In the Ref. [21], Wang *et al.* also proposed an ECP based on quantum dot spins. In their protocol, in each step, they resort two copies of less-entangled pairs. After measuring the photon, at least one pair of less-entangled state should be destroyed, or both pairs should be discarded. In the Ref. [22], they require a single charge qubit and a single photon to reach the same success probability than the first one. In our protocol, we require one pair of less-entangled state and a single photon to reach the same success probability as Refs. [21, 22]. In a practical conditional, this protocol is more powerful. From Eq. (14), the total success probability is related with the efficiency of the transmission and reflection and the photon will be lost if the cavity is imperfect. In this protocol, in each concentration round, the single photon only need to pass through one microcavity while in Ref. [22], it should pass through two microcavities. So it will decrease the total success probability if the cavity leakage is large. Moreover, in his protocol, he should first prepare the assisted single quantum dot on Alice's side in concentration process of the form of  $\alpha|\uparrow\rangle + \beta|\downarrow\rangle$ . In this ECP, we only need to prepare the single photon of the form of Eq. (3). In a practical operation, it is much easier to prepare such single optical qubit. Compared with the ECPs with linear optics [15, 16], only Alice needs to operate the whole steps and this protocol can be repeated to obtain a higher success probability. In our protocol, only one of parties say Alice needs to operate the whole processing. Bob only needs to retain or discard his particles according to the Alice's measurement results.

In summary, we have proposed an optimal ECP with single charged quantum dot inside an optical cavity. It has several advantages: First, they do not need the collective measurement. Second, only one pair of less-entangled state is required. Third, it can be repeated to obtain a higher success probability. Fourth, less operations and classical communications are required. All these advantages may make this ECP useful in current quantum information processing.

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